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(54) **METHODS AND DEVICES FOR ACTIVE OPTICAL CABLE CALIBRATION**

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H01S 5/042	(2006.01)
H01S 5/183	(2006.01)
H04B 10/50	(2013.01)
H01S 5/00	(2006.01)

(52) **U.S. Cl.**

CPC ***H04B 10/504*** (2013.01); ***H04B 10/073*** (2013.01); *H01S 5/0014* (2013.01); *H01S 5/042* (2013.01); *H01S 5/183* (2013.01)

(58) **Field of Classification Search**

CPC H01S 5/423; H04B 10/073; H04B 10/504
USPC 385/14; 375/371
See application file for complete search history.

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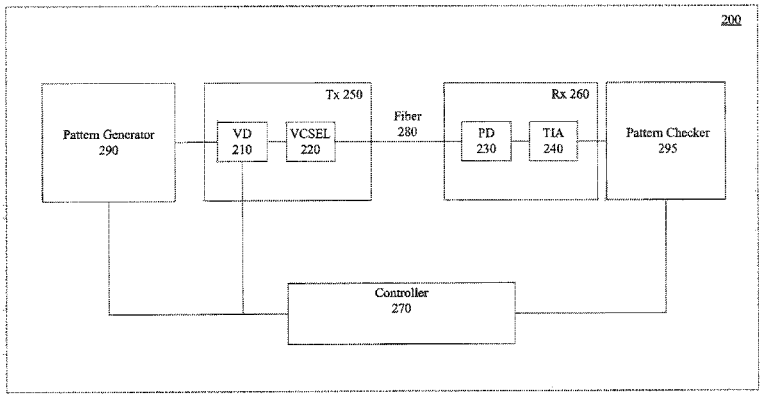
(57) **ABSTRACT**

Methods and devices for laser driver calibration are disclosed. The methods and devices disclose determining first and second bit error rates for use in calibrating the laser driver. The methods and devices also disclose that if the first bit error rate associated with a first initial value is above a predetermined bit error rate, increasing the first initial value until the first bit error rate is not above the predetermined bit error rate, and if the second bit error rate associated with a second initial value is above a predetermined bit error rate, decreasing the second initial value until the second bit error rate is not above the predetermined bit error rate. In addition, the methods and devices disclose setting a calibrated parameter for the laser driver based, at least in part, on the increased first initial value and the decreased second initial value.

21 Claims, 10 Drawing Sheets



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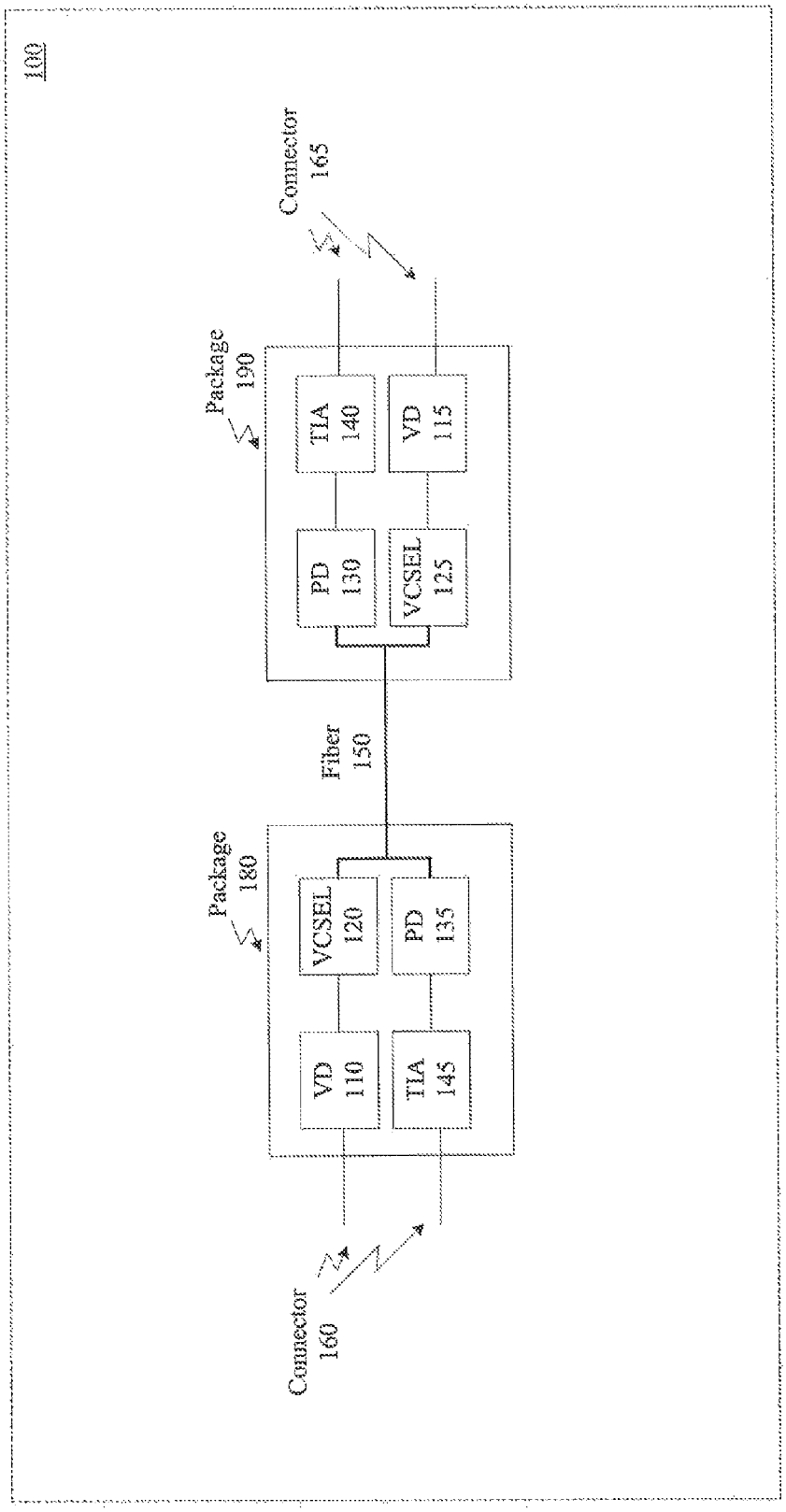
100
Connector 165
Package 190
TIA 140
VD 115
PD 130
VCSEL 125
Fiber 150
Package 180
VCSEL 120
PD 135
VD 110
TIA 145
Connector 160

Figure 1

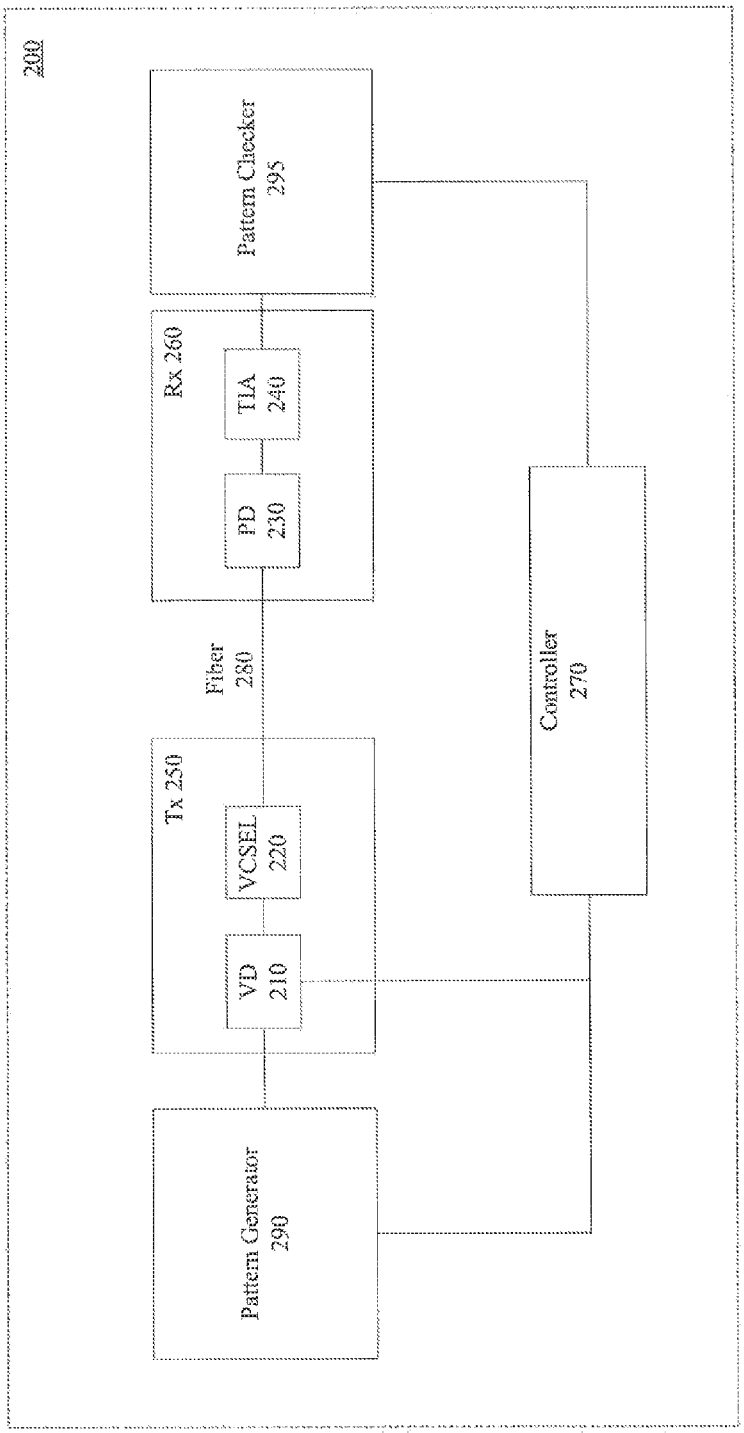
200
Pattern Checker
295
Rx 260
TIA
240
PD
230
Fiber
280
Tx 250
VCSEL
220
VD
210
Pattern Generator
290
Controller
270

Figure 2

300

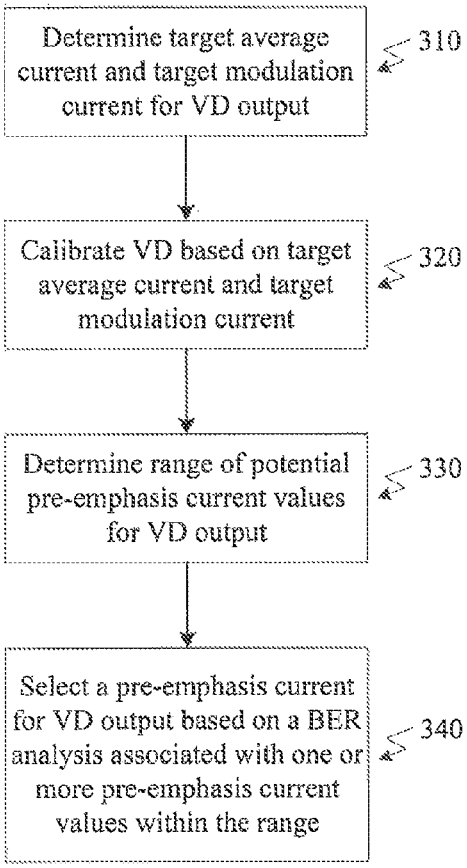
Determine target average current and target modulation current for VD output
310
Calibrate VD based on target average current and target modulation current
320
Determine range of potential pre-emphasis current values for VD output
330
Select a pre-emphasis current for VD output based on a BER analysis associated with one or more pre-emphasis current values within the range
340

Figure 3

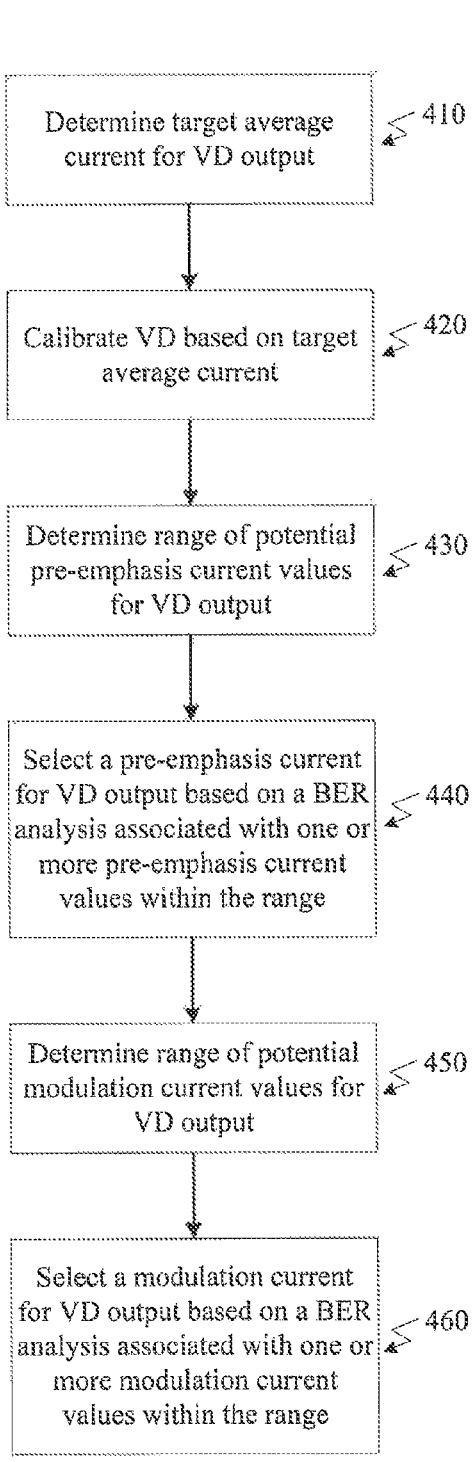
400
Determine target average current for VD output
410
Calibrate VD based on target average current
420
Determine range of potential pre-emphasis current values for VD output
430
Select a pre-emphasis current for VD output based on a BER analysis associated with one or more pre-emphasis current values within the range
440
Determine range of potential modulation current values for VD output
450
Select a modulation current for VD output based on a BER analysis associated with one or more modulation current values within the range
460

Figure 4

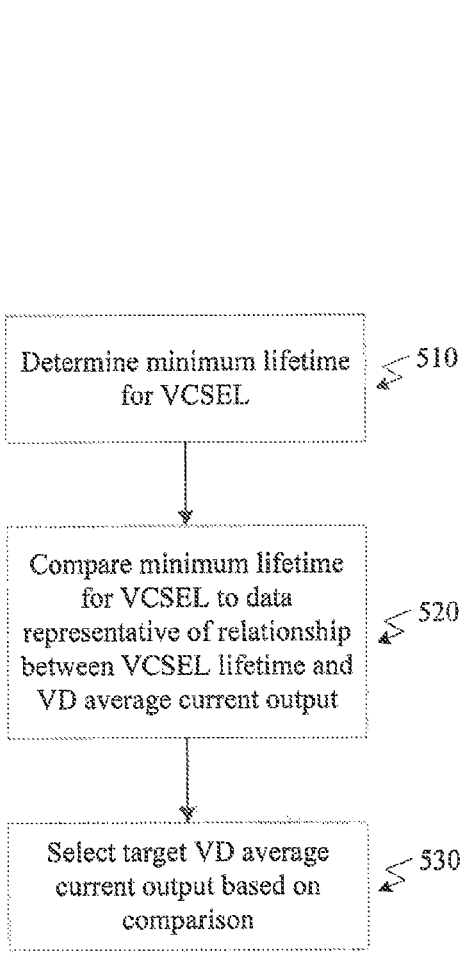
500
Determine minimum lifetime for VCSEL
510
Compare minimum lifetime for VCSEL to data representative of relationship between VCSEL lifetime and VD average current output
520
Select target VD average current output based on comparison
530

Figure 5

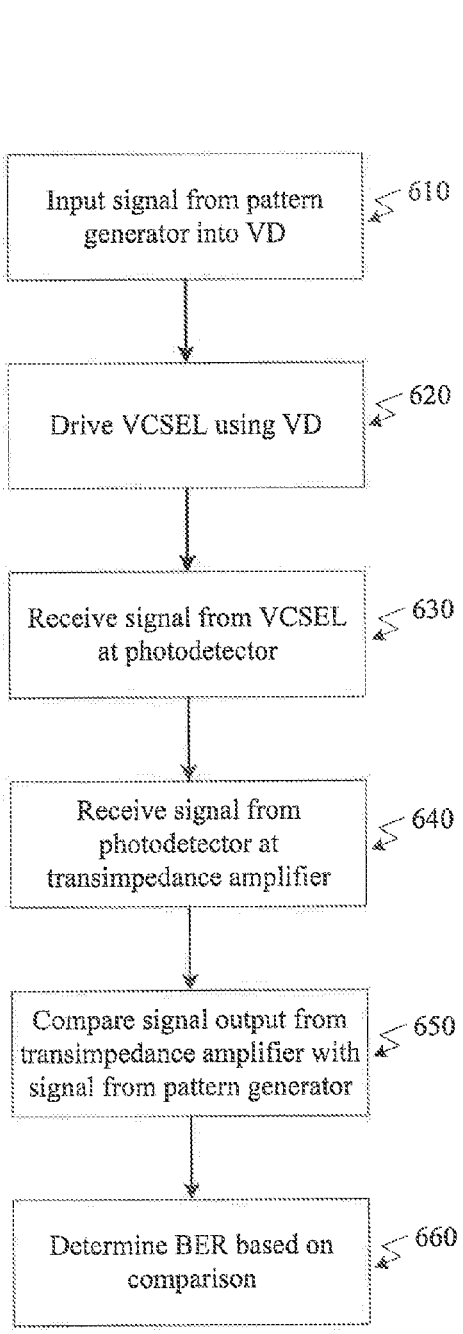
600
Input signal from pattern generator into VD
610
Drive VCSEL using VD
620
Receive signal from VCSEL at photodetector
630
Receive signal from photodetector at transimpedance amplifier
640
Compare signal output from transimpedance amplifier with signal from pattern generator
650
Determine BER based on comparison
660

Figure 6

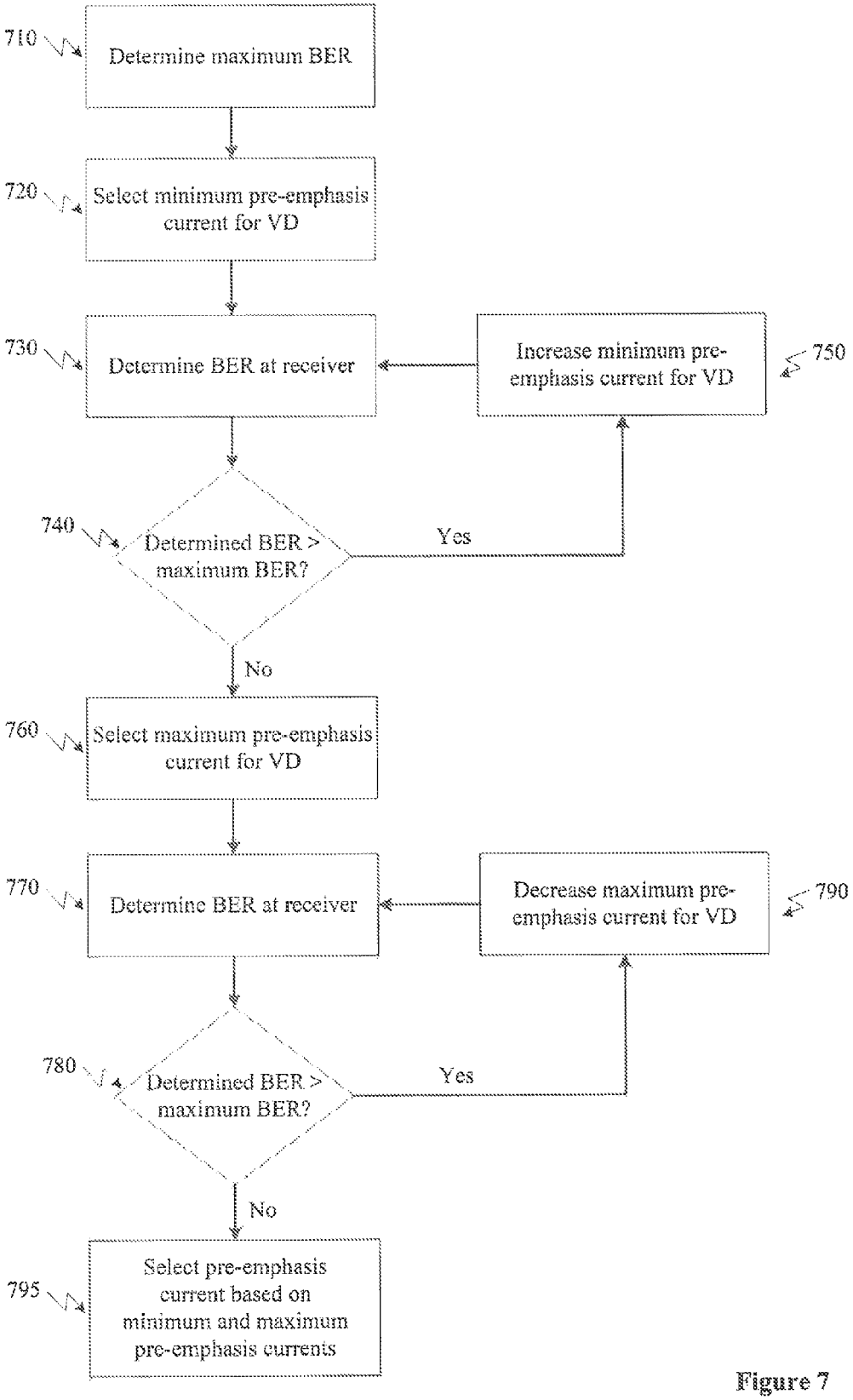
700
710
Determine maximum BER
720
Select minimum pre-emphasis current for VD
730
Determine BER at receiver
750
Increase minimum pre-emphasis current for VD
740
Determined BER > maximum BER?
Yes
No
760
Select maximum pre-emphasis current for VD
770
Determine BER at receiver
790
Decrease maximum pre-emphasis current for VD
780
Determined BER > maximum BER?
Yes
No
795
Select pre-emphasis current based on minimum and maximum pre-emphasis currents

Figure 7

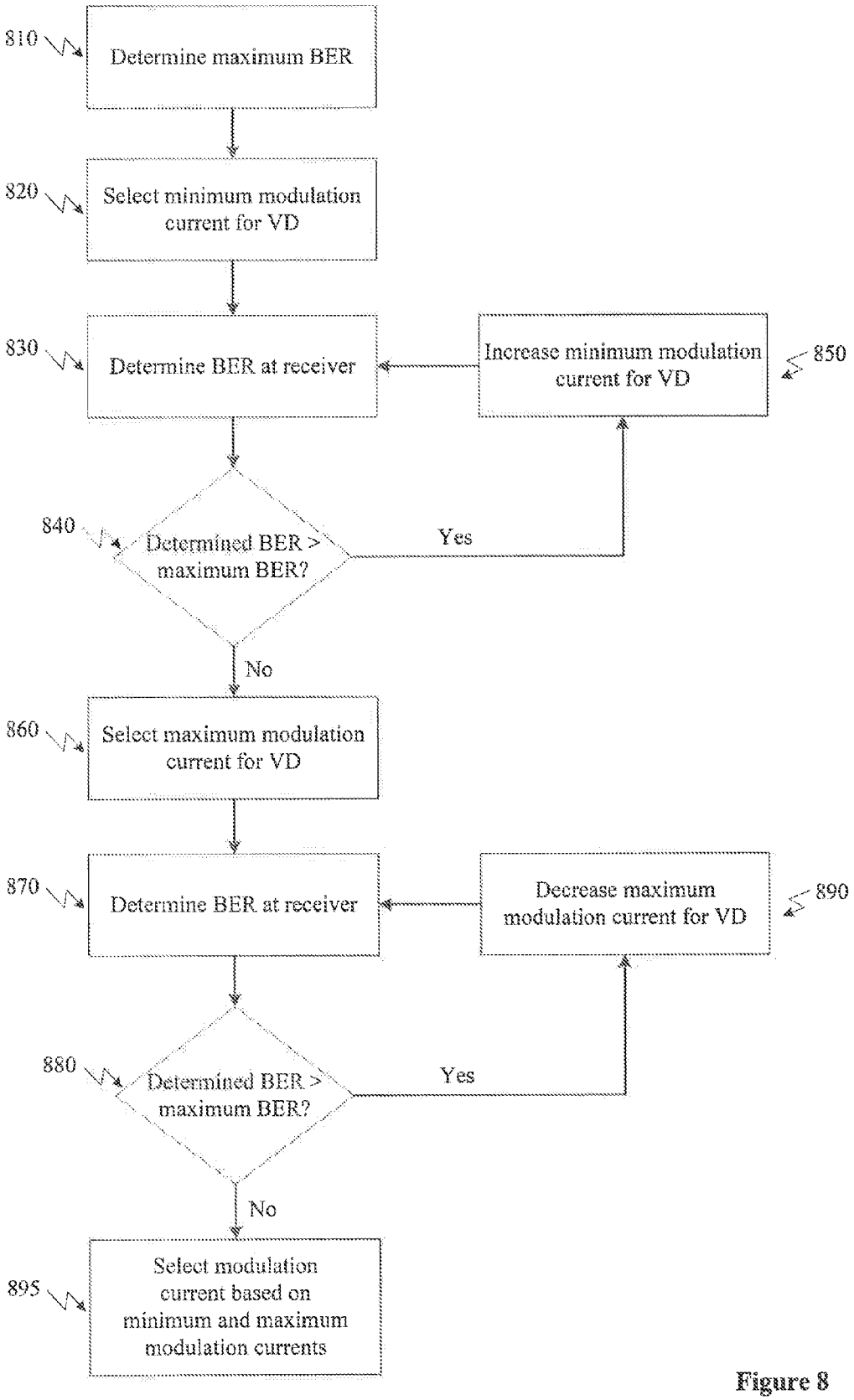
800
810
Determine maximum BER
820
Select minimum modulation current for VD
830
Determine BER at receiver
850
Increase minimum modulation current for VD
840
Determined BER > maximum BER?
Yes
No
860
Select maximum modulation current for VD
870
Determine BER at receiver
890
Decrease maximum modulation current for VD
880
Determined BER > maximum BER?
Yes
No
895
Select modulation current based on minimum and maximum modulation currents

Figure 8

900

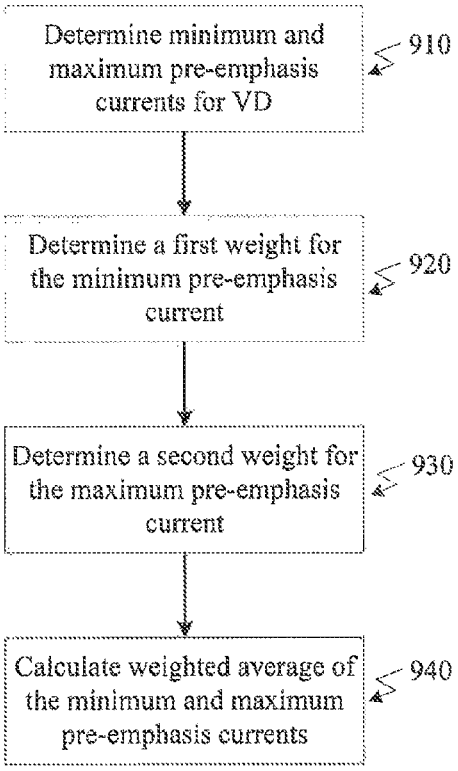
Determine minimum and maximum pre-emphasis currents for VD
910
Determine a first weight for the minimum pre-emphasis current
920
Determine a second weight for the maximum pre-emphasis current
930
Calculate weighted average of the minimum and maximum pre-emphasis currents
940

Figure 9

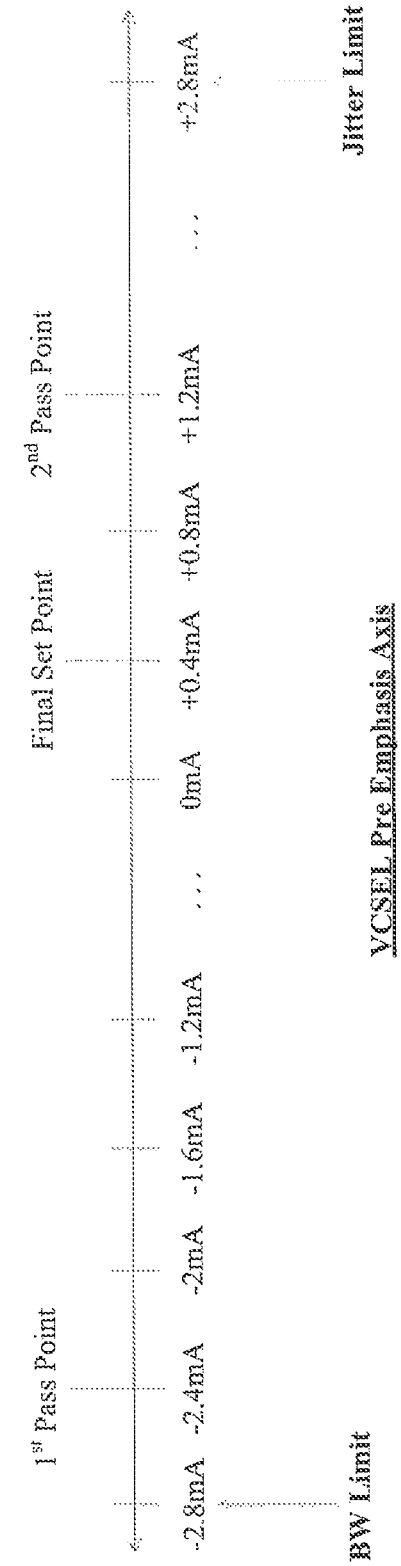
1st Pass Point
2nd Pass Point
Final Set Point
-2.8mA
-2.4mA
-2mA
-1.6mA
-1.2mA
0mA
+0.4mA
+0.8mA
+1.2mA
+2.8mA
BW Limit
Jitter Limit
VCSEL Pre Emphasis Axis

Figure 10

METHODS AND DEVICES FOR ACTIVE OPTICAL CABLE CALIBRATION

TECHNICAL FIELD

The present disclosure relates to the field of active optical cable calibration and, more particularly, methods, systems, and devices for calibrating a laser driver.

BACKGROUND

Optical fiber cables are used in a variety of fields, such as, for example, telecommunications and computer networking. Optical fiber cables often provide a number of benefits over electrical cables, such as, for example, higher bandwidth and reduced interference from external noise. To transmit data over an optical fiber cable between two electrical systems, an optical transceiver is often needed to connect each electrical system to the optical fiber cable. However, many computer systems do to include dedicated optical transceivers.

Active optical cables, which include built-in optical transceivers at both ends of the optical fiber cable, are often used instead of dedicated optical transceivers. Such active optical cables can be plugged into electrical components, such as, for example, network ports. In particular, active optical cables are often configured to have the same or similar physical dimensions to traditional electrical cables such that traditional electrical cables can be more easily replaced with active optical cables. Thus, active optical cables are often used to provide a user with an easy way to replace traditional electrical cables while gaining the benefits of optical fiber cables.

Often, a transmitter of an optical transceiver includes a laser, such as a vertical cavity surface-emitting laser ("VCSEL"), and a laser driver. A laser driver typically includes various configurable parameters that affect the current output from the laser driver into the laser. By adjusting the parameters of the laser driver, the performance of the active optical cable can likewise be adjusted. However, because an active optical cable typically includes various electrical, optical, electro-optical, and mechanical components, variability in the various components that make up an active optical cable often makes each active optical cable unique. Thus, for a group of active optical cables being manufactured, configuring all laser drivers to have the same parameter settings will often result in poor active optical cable performance. Thus, to achieve optimal data transmission with active optical cables, laser driver calibration often needs to be performed on an individual laser driver basis.

Existing techniques for calibrating laser drivers of active optical cables rely on assumptions that are often inaccurate and imprecise. For example, one technique for calibrating a laser driver is to input a signal into the laser driver and view the signal output from the laser driven by the laser driver on an oscilloscope. The parameters of the laser driver may then be adjusted until the signal displayed on the oscilloscope reaches predetermined characteristics. However, the relationship between the signal displayed on an oscilloscope and the performance of an active optical cable is often imprecise and inaccurate.

Improvements in active optical cable calibration technology, including technology that more precisely calibrates a laser driver of an active optical cable, are desirable.

SUMMARY

In one disclosed embodiment, a method for calibrating a laser driver is disclosed. The method comprises determining first and second bit error rates for use in calibrating the laser driver. In addition, the method comprises, if the first bit error rate associated with a first initial value is above a predetermined bit error rate, increasing the first initial value until the first bit error rate is not above the predetermined bit error rate. In addition, the method comprises, if the second bit error rate associated with a second initial value is above a predetermined bit error rate, decreasing the second initial value until the second bit error rate is not above the predetermined bit error rate. In addition, the method comprises setting a calibrated parameter for the laser driver based, at least in part, on the increased first initial value and the decreased second initial value.

In another disclosed embodiment, a laser driver is disclosed. The laser driver is calibrated by determining first and second bit error rates for use in calibrating the laser driver, if the first bit error rate associated with a first initial value is above a predetermined bit error rate, increasing the first initial value until the first bit error rate is not above the predetermined bit error rate, if the second bit error rate associated with a second initial value is above a predetermined bit error rate, decreasing the second initial value until the second bit error rate is not above the predetermined bit error rate, and setting a calibrated parameter for the laser driver based, at least in part, on the increased first initial value and the decreased second initial value.

Additional aspects related to the embodiments will be set forth in part in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an example active optical cable that may be used for implementing the disclosed embodiments.

FIG. **2** illustrates an example system that may be used for implementing the disclosed embodiments.

FIG. **3** illustrates an example method for selecting a preemphasis current for a VCSEL driver based on a bit error rate technique.

FIG. **4** illustrates an example method for selecting a preemphasis current and a modulation current for a VCSEL driver based on a bit error rate technique.

FIG. **5** illustrates an example method for selecting an average current for a VCSEL driver.

FIG. **6** illustrates an example method for determining a bit error rate.

FIG. **7** illustrates an example method for selecting a preemphasis current for a VCSEL driver based on a bit error rate technique.

FIG. **8** illustrates an example method for selecting a modulation current for a VCSEL driver based on a bit error rate technique.

FIG. **9** illustrates an example method for selecting a preemphasis current for a VCSEL driver based on a bit error rate technique.

FIG. **10** illustrates an example plot of data from a preemphasis current selection process.

DETAILED DESCRIPTION

Reference will now be made in detail to the exemplary embodiments, examples of which are illustrated in the

accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

Active optical cable calibration can he improved by implementing bit error rate analysis techniques. In some disclosed embodiments, an average current, a modulation current, and a pre-emphasis current for an output of a laser driver are calibrated. In some disclosed embodiments, the average current is set based on an intended lifetime for a laser driven by the laser driver. In addition, in some disclosed embodiments, the modulation current and/or the pre-emphasis current are set based on a bit error rate analysis.

In some disclosed embodiments, the bit error rate analysis includes setting an initial minimum value for a parameter of the laser driver, measuring a bit error rate, and if the measured bit error rate is above a predetermined bit error rate, increasing the minimum value for the parameter until the bit error rate is not above the predetermined bit error rate. In addition, in some disclosed embodiments, the bit error rate analysis includes setting an initial maximum value for the parameter of the laser driver, measuring a bit error rate, and if the measured bit error rate is above a predetermined bit error rate, decreasing the maximum value for the parameter until the bit error rate is not above the predetermined bit error rate. In some disclosed embodiments, the bit error rate analysis includes setting the parameter of the laser driver based, at least in part, on the increased minimum value and the decreased maximum value. In embodiments in which the parameter of the laser driver that is set based on a bit error rate analysis is the pre-emphasis current, the initial minimum value may be selected based on a bandwidth limit for the active optical cable and the initial maximum value may be selected based on a jitter limit for the active optical cable.

FIG. **1** is a diagram illustrating an example active optical cable **100** according to some disclosed embodiments. Active optical cable **100** may include a package **180** and a package **190** connected by one or more optical fiber cables **150**. In some embodiments, package **180** includes a connector **160**. Connector **160** may be configured, for example, to connect to a network port such as an Ethernet, InfiniBand, or Peripheral Component Interconnect Express port. Connector **160** may also be configured, for example, to connect to electrical components that transmit and/or receive electrical data other than network ports. In some embodiments, connector **160** includes a number of lines for transmitting and/or receiving data. For example, as depicted in FIG. **1**, connector **160** may comprise two lines, with one line for transmitting data and one line for receiving data. In alternative embodiments, connector **160** may include more than one line for transmitting data, more than one line for receiving data, no lines for transmitting data, and/or no lines for receiving data. In some embodiments, package **190** includes a connector **165** configured in substantially the same manner as connector **160**.

In some embodiments, package **180** and package **190** have a pluggable form factor. For example, package **180** and package **190** may be Quad Small Form-factor Pluggable ("QSFP") transceivers, enhanced Quad Small Form-factor Pluggable ("QSFP+") transceivers, Small Form-factor Pluggable ("SFP") transceivers, or enhanced Small Form-factor Pluggable ("SFP+") transceivers.

In some embodiments, one line of connector **160** connects, directly or indirectly, to a vertical cavity surface-emitting laser ("VCSEL") driver **110**. VCSEL driver **110** may control the current supplied to a VCSEL **120** to which VCSEL driver **110** is connected, directly or indirectly. VCSEL driver **110** may be constructed as a circuit such as, for example, an integrated circuit. In alternative embodiments, a different type of laser may replace VCSEL **120**. In some embodiments, one or more parameters of the VCSEL driver **110** are settable. For example, the average current output from the VCSEL driver **110** may be set. In addition, the modulation current output from the VCSEL driver **110**, representative of the difference between the peak and trough of the signal output from the VCSEL driver **110**, may also be set. Moreover, for example, the pre-emphasis current supplied by the VCSEL driver **110**, which may adjust the shape of the signal output from the VCSEL driver **110**, may also be set. In alternative embodiments, additional or alternative parameters of the VCSEL driver **110** may also be set. The parameters of the VCSEL driver **110** may be set in a number of ways such as, for example, using a controller.

In some embodiments, VCSEL driver **110** is capable of encoding the signal supplied from connector **160** onto the current supplied to VCSEL **120**. For example, in some embodiments, the signal supplied from connector **160** may be encoded using frequency modulation, amplitude modulation, or phase modulation. Based on the amount of current supplied to VCSEL **120**, VCSEL **120** may emit a laser output with a laser intensity that corresponds to the current supplied by the VCSEL driver **110**. Thus, the data encoded onto the current supplied by the VCSEL driver **110** may also be encoded on the laser emitted by VCSEL **120**. The laser emitted by VCSEL **120** may propagate, either directly or indirectly via one or more components (e.g., lenses), into a fiber optic cable **150**.

In some embodiments, the light emitted by VCSEL **120** is received by a photo-detector **130** in package **190**. Photo-detector **130** may convert the received light into a corresponding amount of electrical current. In some embodiments, the current output by the photo-detector **130** is then be converted to a voltage by a transimpedance amplifier **140** to which the photo-detector **130** is connected, directly or indirectly, and output using connector **165**.

As depicted in FIG. **1**, in some embodiments package **190** also includes a VCSEL driver **115** and a VCSEL **125**, configured in substantially the same manner as VCSEL driver **110** and VCSEL **120**. Moreover, in some embodiments, package **180** also includes a photo-detector **135** and transimpedance amplifier **145**, configured in substantially the same manner as photo-detector **130** and transimpedance amplifier **140**. Thus, in such embodiments, data can travel in both directions of active optical cable **100**. In some embodiments, fiber optic cable **150** is a multimode cable capable of carrying a plurality of frequencies of light. In such embodiments, a single multimode cable may be used to transmit data in both directions of the active optical cable. However, in alternative embodiments, single-mode cables are used for each transmission line.

While FIG. **1** depicts optical transceivers installed in package **180** and package **190** as part of an active optical cable **100**, in some embodiments an optical transceiver comprising, for example, a laser driver, a laser, a photo-detector, and a transimpedance amplifier, is installed in an optical module that is not part of an active optical cable. For example, an optical transceiver may he installed in an optical engine such as, for example, Mid Board Optics.

FIG. **2** is a diagram illustrating an example system **200** that may be used for implementing the disclosed embodiments. In some embodiments, system **200** may be used for calibrating a VCSEL driver **210** of an active optical cable, such as, for example, active optical cable **100**. System **200** may include a transmitter **250** comprising a VCSEL driver **210** and a VCSEL **220**. In some embodiments, VCSEL driver **210** and VCSEL **220** are configured in substantially the same manner

as described above with respect to VCSEL driver **110** and VCSEL **120**. System **200** may also include a receiver **260**, connected to transmitter **250** by an optical fiber cable **280**, comprising a photo-detector **230** and a transimpedance amplifier **240**. Photo-detector **230**, transimpedance amplifier **240**, and optical fiber cable **280** may be configured in substantially the same manner as photo-detector **130**, transimpedance amplifier **140**, and optical fiber cable **280**, respectively. In some embodiments, transmitter **250** and receiver **260** may be part of an active optical cable, such as active optical cable **100**. For example, VCSEL driver **210** and VCSEL **220** may be VCSEL driver **110** and VCSEL **120** within package **180**, optical fiber cable **280** may be optical fiber cable **150**, and photo-detector **230** and transimpedance amplifier **240** may be photo-detector **130** and transimpedance amplifier **140** within package **190**. Thus, in some embodiments, active optical cable **100** may be included in system **200**. However, in other embodiments, receiver **260** may be a reference receiver that will not be installed in an active optical cable. For example, in some embodiments, system **200** may be used to test a VCSEL driver **210** and VCSEL **220** that are being installed into an active optical cable against a reference receiver. Moreover, in some embodiments, VCSEL driver **210** and VCSEL **220** are tested for use in a laser module rather than an active optical cable. In addition, in some embodiments, a type of laser other than VCSEL **220** is used in place of VCSEL **220**.

System **200** may also include a controller **270**. Controller **270** may be a CPU or some other processor capable of electronically controlling the components of system **200**. In some embodiments, controller **270** may be configured to calibrate the settable parameters of VCSEL driver **210** such as, for example, the average current, the modulation current, and the pre-emphasis current output by the VCSEL driver **210**.

In some embodiments, system **200** also includes a pattern generator **290**. In some embodiments, pattern generator **290** is configured to transmit a signal with a pattern to VCSEL driver **210**. For example, pattern generator **290** may be configured to transmit one or more different pseudo-random bit sequences. In some embodiments, controller **270** is configured to select the pseudo-random bit sequence emitted by the pattern generator **290**. The pattern output by pattern generator **290** may be encoded onto the current that is output by VCSEL driver **210** and, as a result, encoded onto the laser output by VCSEL **220**. In some embodiments, system **200** also includes a pattern checker **295**. Pattern checker may be configured to determine the bit error rate of the signal received by the receiver **260**. For example, pattern checker **295** may be configured to compare the signal received at pattern checker **295** to the signal transmitted by pattern generator **290** to determine the number of errors in the received signal. In some embodiments, the controller **270** signals the type of pattern transmitted by pattern generator **290** to the pattern checker **295** for comparison. In alternative embodiments, pattern generator **290** and pattern checker **295** may be the same component.

FIG. **3** is a diagram illustrating an example method **300** for selecting a pre-emphasis current for a VCSEL driver **210** based on a bit error rate analysis. In some embodiments, method **300** begins by determining a target average current and target modulation current for the output of the VCSEL driver **210**. In some embodiments, the average current is determined based on an intended lifetime for a VCSEL **220** driven by the VCSEL driver **210**.

For example, as depicted in FIG. **5**, a minimum lifetime for the VCSEL **220** may first be determined (step **510**). For example, it may be determined that a minimum VCSEL lifetime of 2 years, 5 years, or 10 years is required. As the average current supplied to the VCSEL **220** increases, the VCSEL lifetime decreases. The relationship between the average current output by a VCSEL driver **210** and VCSEL lifetime may be stored in data. Thus, in some embodiments, the minimum VCSEL lifetime may be compared to the data representative of the relationship between VCSEL lifetime and average current output of a VCSEL driver **210** (step **520**). In some embodiments, the data that is compared to indicates a current value for each VCSEL lifetime value in a set of VCSEL lifetime values such that, if the average current is set at or below the current value amount, the desired VCSEL lifetime will be achieved. The target average current for the output of the VCSEL driver **210** may then be selected based on the comparison (step **530**). For example, if only VCSEL lifetime is considered, the average current may be set at or below the current value amount that achieves the desired VCSEL lifetime.

In some embodiments, factors other than VCSEL lifetime are considered when selecting a target average current output for the VCSEL driver **210**. For example, in some embodiments, bandwidth is maximized for a given intended VCSEL lifetime. Since bandwidth increases as average current output by the VCSEL driver **210** increases, in embodiments in which a target VCSEL lifetime needs to be met and bandwidth needs to be maximized for the target VCSEL lifetime, the maximum average current output that still achieves the target VCSEL lifetime is selected as the target average current. In some embodiments, a margin of error is maintained such that the target average current output is set just below the maximum average current output that still achieves the target VCSEL lifetime to increase the likelihood of the target VCSEL lifetime being achieved.

In some embodiments, the target modulation current for the output of the VCSEL driver **210** may be set as the modulation current that achieves the minimum required extension ratio. In such embodiments, after determining the target average current and target modulation current, the VCSEL driver **210** may be calibrated to achieve the target average current and target modulation current (step **320**). The VCSEL driver **210** may be calibrated by setting the VCSEL driver **210** to utilize various average and modulation currents and measuring corresponding current consumptions from the VCSEL driver's current source. Based on the current consumptions at various average and modulation currents, the relationship between the set average and modulation current of the VCSEL driver **210** and the actual output average and modulation current of the VCSEL driver **210** may be determined. For example, the average current source of the VCSEL driver **210** may be set to 0.1 mA and the current consumed by the VCSEL driver **210** may be measured. Then, the average current source may be set to 10.1 mA and the current consumed by the VCSEL driver **210** may be measured. The difference between the measured current consumed by the VCSEL driver **210** for the two current source values may be interpreted as the actual output average current of the VCSEL driver **210** when the average current of the VCSEL driver **210** is set to 10 mA.

In some embodiments, an initial range of potential pre-emphasis current values for the output of the VCSEL driver is then determined (step **330**). For example, if the pre-emphasis current value is set too low, bandwidth may be too low for the requirements of the active optical cable. However, if the pre-emphasis current value is set too high, jitter may be too high for the requirements of the active optical cable. Thus, based on the maximum allowable jitter and the minimum allowable

bandwidth, an initial range of acceptable potential pre emphasis current values is determined.

After determining the range of acceptable potential pre-emphasis current values, a pre-emphasis current for the output of the VCSEL driver **210** may be selected based on a bit error rate analysis (step **340**). For example, as described in more detail below, the bit error rate resulting from setting the VCSEL driver **210** with each of a set of pre-emphasis current values may be determined and analyzed to select a pre-emphasis current for the VCSEL driver **210**.

While FIG. **3** depicts the pre-emphasis current being selected based on a bit error rate analysis, different parameters of the VCSEL driver **210** may also be selected based on a bit error rate analysis in substantially the same manner. For example, a target pre-emphasis current may be selected without a bit error rate analysis and a modulation current for the VCSEL driver **210** may be selected based on a bit error rate analysis.

FIG. **4** is a diagram illustrating an example method **400** for selecting a pre-emphasis current and a modulation current for a VCSEL driver **210** based on a bit error rate analysis. In some embodiments, method **400** begins by determining a target average current for the VCSEL driver **210** (step **410**), in substantially the same manner as the target average current is determined in step **310** of method **300**. In addition, in some embodiments the VCSEL driver **210** is calibrated based on the target average current (step **420**), in substantially the same manner as the calibration is performed step **320** of method **300**. After calibrating the average current of the VCSEL driver **210**, in some embodiments an initial range of potential pre-emphasis current values is determined (step **430**), in substantially the same manner as the range is determined in step **330** of method **300**. Moreover, a pre-emphasis current value may be selected for the VCSEL driver **210** using a bit error rate analysis (step **440**), in substantially the same manner as the pre-emphasis current value is selected in step **340** of method **300**.

In some embodiments, an initial range of acceptable modulation current values is then determined (step **450**). For example, one or more modulation current values between a minimum required extension ratio and a maximum acceptable extension ratio may be included in the initial range of acceptable modulation current values. Then, in some embodiments, a modulation current for the VCSEL driver **210** may be selected based on a bit error rate analysis (step **460**). In some embodiments, the bit error rate analysis of step **460** may be performed in substantially the same manner as the bit error rate analysis of step **440**. Thus, in some embodiments, rather than determining a target modulation current without a bit error rate analysis (e.g., as described above with respect to steps **310** and **320** of method **300**), the modulation current for the VCSEL driver **210** is selected based on a bit error rate analysis. For example, as described in more detail below, the bit error rate resulting from setting the VCSEL driver **210** with each of a set of modulation current values may be determined and analyzed to select a modulation current for the VCSEL driver **210**.

While FIG. **4** depicts the pre-emphasis current as being selected (steps **430** and **440**) before the modulation current is selected (steps **450** and **460**), in alternative embodiments the modulation current may be selected (steps **450** and **460**) before the pre-emphasis current is selected (steps **430** and **440**). Moreover, in some embodiments, other parameters of the VCSEL driver **210** are also configured using non-bit error rate and/or bit error rate analysis.

FIG. **6** is a diagram illustrating an example method **600** for determining a bit error rate associated with an active optical cable transmitter. In some embodiments, method **600** begins with a signal from a pattern generator **290** being input into a VCSEL driver **210** (step **610**). As described above, in some embodiments the signal from pattern generator **290** is a pseudo-random bit sequence. In some embodiments, current encoded with the pseudo-random bit sequence is output from VCSEL driver **210** to VCSEL **220** (step **620**). In some embodiments, VCSEL **220** emits a laser, with an intensity based on the received current at the VCSEL **220**, which propagates through a fiber optical cable **280** and is received at a photo-detector **230** (step **630**). In some embodiments, a transimpedance amplifier **240** receives current output by photo-detector **230** and outputs a voltage corresponding to the received current (step **640**). The signal output by the transimpedance amplifier to a pattern checker **295** may then be compared to the signal output by pattern generator **290** (step **650**). For example, both the signal output by the transimpedance amplifier and the signal output by pattern generator **290** may be converted to binary data and the number of differences and matches between the binary data may be determined. Based on the comparison between the signal output by pattern generator **290** and the signal received by pattern checker **295**, the bit error rate may be determined (step **660**). For example, the bit error rate may be set as the number of differences divided by a combination of the number of difference and number of matches.

FIG. **7** is a diagram illustrating an example method **700** for selecting a pre-emphasis current for a VCSEL driver **210** based on a bit error rate analysis. In some embodiments, method **700** begins with a determination of the maximum acceptable bit error rate (step **710**). For example, some active optical cables may have a relatively high maximum acceptable bit error rate, while other active optical cables may have a relatively low maximum acceptable bit error rate. Then, an initial minimum pre-emphasis current for the VCSEL driver **210** may be selected (step **720**). For example, as depicted in the example of FIG. **10**, if the pre-emphasis current is set too low, the bandwidth of an active optical cable may go below a bandwidth limit. Thus, in some embodiments, the initial minimum pre-emphasis current is set at or above a pre-emphasis current that achieves the bandwidth limit. Thus, in the example depicted in FIG. **10**, the initial minimum pre-emphasis current may be set at −2.8 mA, which is representative of the pre-emphasis current that results in a minimum acceptable bandwidth. A controller, such as, for example, controller **270**, may be used to configure VCSEL driver **210** to utilize the initial minimum pre-emphasis current.

In some embodiments, a bit error rate associated with the VCSEL driver **210** is then measured using a process, for example, as described above with respect to method **600** (step **730**). A determination may then be made as to whether the determined bit error rate is above the maximum acceptable bit error rate (step **740**). If the determined bit error rate is above the maximum acceptable bit error, the pre-emphasis current of the VCSEL driver **210** may then be increased (step **750**). In some embodiments, the pre-emphasis current may be increased by a predetermined amount (e.g., each time the pre-emphasis current is increased, it may always be increased by the same amount, such as, for example, 0.4 mA). In other embodiments, the pre-emphasis current may be increased by an amount based on the determined bit-error rate (e.g., the pre-emphasis current may be increased a relatively large amount if the difference between the determined bit error rate and the maximum acceptable bit error is relatively large, whereas the pre-emphasis current may be increased a relatively small amount if the difference between the determined bit error rate and the maximum acceptable bit error rate is

relatively small). In some embodiments, steps **730-750** may be repeated until the determined bit error rate is at or below the maximum acceptable bit error rate. In the example depicted in FIG. **10**, the pre-emphasis current may be increased by 0.4 mA with each repetition of steps **730-750**. The first pre-emphasis current that results in a bit error rate below the maximum acceptable bit error rate may be kept as a first pass point. In the example of FIG. **10**, a pre-emphasis current of −2.4 mA results in a bit error rate below the maximum acceptable bit error rate and is kept as a first pass point. In some embodiments, if no pre-emphasis current is found that results in a bit error rate below the maximum acceptable bit error rate, the maximum acceptable bit error rate is decreased.

In some embodiments, an initial maximum pre-emphasis current for the VCSEL driver **210** may be selected (step **760**). For example, as depicted in FIG. **10**, if the pre-emphasis current is too high, the jitter of an active optical cable may go above a jitter limit. Thus, the initial maximum pre-emphasis current may be set at or below a pre-emphasis current that achieves the jitter limit. Thus, as depicted in the example of FIG. **10**, the initial maximum pre-emphasis current may be set at 2.8 mA, which is representative of the pre-emphasis current that results in a maximum acceptable jitter. While in the example of FIG. **10**, the jitter limit and the bandwidth limit are opposite values (i.e., the jitter limit is 2.8 mA and the bandwidth limit is −2.8 mA), the initial minimum pre-emphasis current and the initial maximum pre-emphasis current are not necessarily opposites. A controller, such as, for example, controller **270**, may be used to configure VCSEL driver **210** to utilize the initial maximum pre-emphasis current.

In some embodiments, a bit error rate associated with the VCSEL driver **210** is then measured using a process, for example, as described above with respect to method **600** (step **770**). A determination may then be made as to whether the determined bit error rate is above the maximum acceptable bit error rate (step **780**). If the determined bit error rate is above the maximum acceptable bit error, the pre-emphasis current of the VCSEL driver **210** may then be decreased (step **790**). In some embodiments, the pre-emphasis current may be decreased by a predetermined amount (e.g., each time the pre-emphasis current is decreased, it may always be decreased by the same amount, such as, for example, 0.4 mA). In other embodiments, the pre-emphasis current may be decreased by an amount based on the determined bit-error rate (e.g., the pre-emphasis current may be decreased a relatively large amount if the difference between the determined bit error rate and the maximum acceptable bit error is relatively large, whereas the pre-emphasis current may be decreased a relatively small amount if the difference between the determined bit error rate and the maximum acceptable bit error rate is relatively small). In some embodiments, steps **770-790** may be repeated until the determined bit error rate is at or below the maximum acceptable bit error rate. In the example depicted in FIG. **10**, the pre-emphasis current may be decreased by 0.4 mA with each repetition of steps **770-790**. The first pre-emphasis current that results in a bit error rate below the maximum acceptable bit error rate may be kept as a second pass point. In the example of FIG. **10**, a pre-emphasis current of 1.2 mA results in a bit error rate below the maximum acceptable bit error rate and is kept as a second pass point.

In some embodiments, the pre-emphasis current for the VCSEL driver **210** may then be set as a value selected at or between the first pass point and the second pass point (step **795**). For example, in the example depicted in FIG. **10**, a pre-emphasis current of 0.4 mA is selected for the VCSEL driver **210**. In some embodiments, the pre-emphasis current of the VCSEL driver **210** is permanently set as the selected value. For example, in some embodiments, after the parameters of VCSEL driver **210** are set, the VCSEL driver **210** and VCSEL **220** may be permanently installed in an active optical cable **100** in such a manner that the parameters of VCSEL driver **210** cannot be changed. In other embodiments, the pre-emphasis current is periodically tuned. For example, in some embodiments, the parameters of VCSEL driver **210** may be changed while VCSEL driver **210** and VCSEL **220** are installed in an active optical cable **100**. In embodiments in which the parameters of VCSEL driver **210** may be changed while VCSEL driver **210** and VCSEL **220** are installed in an active optical cable **100**, the method **700** may be repeated in response to an event such as, for example, a change in the average current output by the VCSEL driver **210**, a determination that the bit error rate of the active optical cable **100** has increased above the maximum acceptable bit error rate, and/or a determination that the intended lifetime of the VCSEL **220** has changed.

While FIG. **7** depicts a method for selecting a pre-emphasis current for a VCSEL driver **210**, other parameters of the VCSEL driver **210** may also be selected using a substantially similar process. For example, FIG. **8** illustrates an example method **800** for selecting a modulation current for a VCSEL driver **210** based on a bit error rate analysis. In some embodiments, steps **810-895** of method **800** are performed in substantially the same manner as steps **710-795** of method **700**.

FIG. **9** is a diagram illustrating an example method **900** for selecting a pre-emphasis current for a VCSEL driver **210** based on a first pass point for a minimum pre emphasis current and a second pass point for a maximum pre-emphasis current. In some embodiments, method **900** begins with a determination of a first pass point for a minimum pre emphasis current and a second pass point for a maximum pre-emphasis current, determined, for example, as described above with respect to steps **710-790** of method **700** (step **910**). A first weight may then be determined to apply to the first determined pass point (step **920**) and a second weight may be determined to apply to the second determined pass point (step **930**). In some embodiments, the first weight and the second weight are both set to be equal. For example, if jitter and bandwidth are equally important, the first weight and the second weight may he set to be equal. In other embodiments, the first weight and second weight are set as different values. For example, in embodiments in which a high bandwidth is more important than a low jitter, the second weight may be greater than the first weight. Alternatively, for example, in embodiments in which a low jitter is more important than a high bandwidth, the first weight may be greater than the second weight. After determining the first and second weight, a weighted average of the minimum and maximum pre-emphasis currents may be calculated (step **940**). In some embodiments, the calculated weighted average may be set as the pre-emphasis current of the VCSEL driver **210**. In other embodiments, the weighted average may be rounded to a certain nearest value and then set as the pre-emphasis current of the VCSEL driver **210**. For example, the weighted average may be rounded to the nearest 0.4 mA (e.g., if the weighted average equals 2.1 mA, then the pre-emphasis current of the VCSEL driver **210** may be set to 2.0 mA, whereas if the weighted average equals 2.3 mA, then the pre-emphasis current of the VCSEL driver **210** may be set to 2.4 mA).

Several embodiments are described above with respect to a VCSEL driver and VCSEL installed in an active optical cable. As described above, active optical cables may provide a number of benefits over traditional electrical cables. However, a

VCSEL driver and VCSEL for a laser module, rather than an active optical cable, may also be calibrated using the disclosed techniques. Moreover, a type of laser and laser driver other than a VCSEL and VCSEL driver may also be calibrated using the disclosed techniques.

Embodiments and all of the functional operations described in this specification can be implemented in digital electronic circuitry, or in computer software, firmware, or hardware, including the structures disclosed in this specification and their structural equivalents, or in combinations of them. Embodiments can be implemented as one or more computer program products, i.e., one or more modules of computer program instructions encoded on a computer readable medium, e.g., a machine readable storage device, a machine readable storage medium, a memory device, or a machine readable propagated signal, for execution by, or to control the operation of, data processing apparatus.

The term "data processing apparatus" encompasses all apparatus, devices, and machines for processing data, including by way of example a programmable processor, a computer, or multiple processors or computers. The apparatus can include, in addition to hardware, code that creates an execution environment for the computer program in question, e.g., code that constitutes processor firmware, a protocol stack, a database management system, an operating system, or a combination of them. A propagated signal is an artificially generated signal, e.g., a machine-generated electrical, optical, or electromagnetic signal, which is generated to encode information for transmission to suitable receiver apparatus.

A computer program (also referred to as a program, software, an application, a software application, a script, or code) can he written in any form of programming language, including compiled or interpreted languages, and it can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment. A computer program does not necessarily correspond to a file in a file system. A program can be stored in a portion of a file that holds other programs or data (e.g., one or more scripts stored in a markup language document), in a single file dedicated to the program in question, or in multiple coordinated files (e.g., files that store one or more modules, sub programs, or portions of code). A computer program can be deployed to be executed on one computer or on multiple computers that are located at one site or distributed across multiple sites and interconnected by a communication network.

The processes and logic flows described in this specification can be performed by one or more programmable processors executing one or more computer programs to perform functions by operating on input data and generating output. The processes and logic flows can also be performed by, and apparatus can also be implemented as, special purpose logic circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application specific integrated circuit).

Processors suitable for the execution of a computer program include, by way of example, both general and special purpose microprocessors, and any one or more processors of any kind of digital computer. Generally, a processor will receive instructions and data from a read only memory or a random access memory or both. The essential elements of a computer are a processor for executing instructions and one or more memory devices for storing instructions and data. Generally, a computer will also include, or be operatively coupled to, a communication interface to receive data from or transfer data to, or both, one or more mass storage devices for storing data, e.g., magnetic, magneto optical disks, or optical disks.

Moreover, a computer can be embedded in another device. Information carriers suitable for embodying computer program instructions and data include all forms of non volatile memory, including by way of example semiconductor memory devices, e.g., EPROM, EEPROM, and flash memory devices; magnetic disks, e.g., internal hard disks or removable disks; magneto optical disks; and CD ROM and DVDROM disks. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

To provide for interaction with a user, embodiments of the invention can be implemented on a computer having a display device, e.g., a CRT (cathode ray tube) or LCD (liquid crystal display) monitor, for displaying information to the user and a keyboard and a pointing device, e.g., a mouse or a trackball, by which the user can provide input to the computer. Other kinds of devices can be used to provide for interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback, e.g., visual feedback, auditory feedback, or tactile feedback; and input from the user can be received in any form, including acoustic, speech, or tactile input.

Embodiments can be implemented in a computing system that includes a back end component, e.g., as a data server, or that includes a middleware component, e.g., an application server, or that includes a front end component, e.g., a client computer having a graphical user interface or a Web browser through which a user can interact with an implementation of the invention, or any combination of such back end, middleware, or front end components. The components of the system can be interconnected by any form or medium of digital data communication, e.g., a communication network. Examples of communication networks include a local area network ("LAN") and a wide area network ("WAN"), e.g., the Internet.

The computing system can include clients and servers. A client and server are generally remote from each other and typically interact through a communication network. The relationship of client and server arises by virtue of computer programs running on the respective computers and having a client/server relationship to each other.

Certain features which, for clarity, are described in this specification in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features which, for brevity, are described in the context of a single embodiment, may also be provided in multiple embodiments separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

Particular embodiments have been described. Other embodiments are within the scope of the following claims.

What is claimed is:

1. A method for calibrating a laser driver, comprising:

determining first and second bit error rates for use in calibrating the laser driver;

selecting a first initial value associated with the first bit error rate based on an intended minimum bandwidth and selecting a second initial value associated with the second bit error rate based on an intended maximum jitter;

if the first bit error rate is above a predetermined bit error rate, increasing the first initial value until the first bit error rate is not above the predetermined bit error rate;

if the second bit error rate is above the predetermined bit error rate, decreasing the second initial value until the second bit error rate is not above the predetermined bit error rate; and

setting a calibrated parameter for the laser driver based, at least in part, on the increased first initial value and the decreased second initial value.

2. The method of claim **1**, wherein determining the first and second bit error rates further comprises:

inputting a first signal to the laser driver;

receiving a second signal, wherein the second signal is based, at least in part, on an output from the laser driver; and

comparing the first signal to the second signal.

3. The method of claim **2**, further comprising:

inputting the output from the laser driver to a laser;

receiving light from the laser at a receiver; and

generating the second signal at the receiver.

4. The method of claim **3**, wherein the laser is a vertical cavity surface-emitting laser.

5. The method of claim **3**, wherein the light is received from the laser at the receiver via an optical fiber cable.

6. The method of claim **1**, wherein the parameter is a pre-emphasis current associated with the laser driver.

7. The method of claim **1**, wherein the parameter is a modulation current associated with the laser driver.

8. The method of claim **1**, further comprising setting an average current output by the laser driver before setting the calibrated value for the parameter.

9. The method of claim **8**, wherein the average current output is selected based, at least in part, on the intended lifetime for a laser driven by the laser driver.

10. A laser driver, wherein the laser driver is calibrated by performing the steps of:

determining first and second bit error rates for use in calibrating the laser driver;

selecting a first initial value for the first bit error rate based on an intended minimum bandwidth and selecting a second initial value for the second bit error rate based on an intended maximum jitter;

if the first bit error rate is above a predetermined bit error rate, increasing the first initial value until the first bit error rate is not above the predetermined bit error rate;

if the second bit error rate is above the predetermined bit error rate, decreasing the second initial value until the second bit error rate is not above the predetermined bit error rate; and

setting a calibrated parameter for the laser driver based, at least in part, on the increased first initial value and the decreased second initial value.

11. The laser driver of claim **10**, wherein determining the first and second bit error rates further comprises:

inputting a first signal to the laser driver;

receiving a second signal, wherein the second signal is based, at least in part, on an output from the laser driver; and

comparing the first signal to the second signal.

12. The laser driver of claim **11**, wherein the laser driver is further calibrated by performing the steps of:

inputting the output from the laser driver to the laser;

receiving light from the laser at a receiver; and

generating the second signal at the receiver.

13. The laser driver of claim **12**, wherein the laser is a vertical cavity surface-emitting laser.

14. The laser driver of claim **10**, wherein the parameter is a pre-emphasis current associated with the laser driver.

15. The laser driver of claim **10**, wherein the parameter is a modulation current associated with the laser driver.

16. The laser driver of claim **10**, wherein the laser driver is further calibrated by performing the step of setting an average current output by the laser driver before setting the calibrated value for the parameter.

17. The laser driver of claim **16**, wherein the average current output is selected based, at least in part, on the intended lifetime for a laser driven by the laser driver.

18. The laser driver of claim **10**, wherein the laser driver is installed in an active optical cable.

19. The laser driver of claim **10**, wherein the laser driver is installed in a Quad Small Form factor Pluggable transceiver or an enhanced Quad Small Form-factor Pluggable transceiver.

20. The laser driver of claim **10**, wherein the laser driver is installed in a Small Form factor Pluggable transceiver or an enhanced Small Form-factor Pluggable transceiver.

21. The laser driver of claim **10**, wherein the laser driver is installed in an optical engine.

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